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Welcome from Editor

It is my pleasure to bring to you the compiled papers from the Science Day of the AFAC and Bushfire CRC Annual Conference, held in the Sydney Convention Centre on the 1st of September 2011.

These papers were anonymously referred. I would like to express my gratitude to all the referees who agreed to take on this task diligently. I would also like to extend my gratitude to all those involved in the organising, and conducting of the Science Day.

The range of papers spans many different disciplines, and really reflects the breadth of the work being undertaken, The Science Day ran four steams covering Fire behaviour and weather; Operations; Land Management and Social Science. Not all papers presented are included in these proceedings as some authors opted to not supply full papers.

The full presentations from the Science Day and the posters from the Bushfire CRC are available on the Bushfire CRC website www.bushfirecrc.com.

Richard Thornton

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The effect of prescribed fire severity and burn patchiness on runoff and erosion

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Abstract

Fire severity and burn patchiness – potentially important factors influencing post-fire surface runoff and erosion – are controlled by fire managers to some extent during prescribed burning. A better understanding of this influence could improve burning practices to minimise water quality impacts. In this study 116 unbounded runoff samplers (opening 10 cm wide; ~ 100 m from catchment divide) were installed on six hillslopes beneath: (1) high fire severity (shrubs burnt; canopy scorched), (2) low fire severity (shrubs scorched or burnt; canopy intact), (3) unburnt, and low fire severity above (4) 1 m, (5) 5 m, and (6) 10 m wide unburnt patches. Runoff volume and sediment load were measured on 27 occasions over 16 months. The sediment loads on the burnt hillslopes were approximately four orders of magnitude larger than on the unburnt hillslope, while there was a 13% difference in sediment load between the high and low fire severities. Much larger loads for the burnt hillslopes could equate to large increases in the total suspended sediment load in streams if the entire catchment were burnt. However, prescribed burns are usually patchy. Measurements on patchily burnt hillslopes found that unburnt patches were highly effective at reducing runoff and sediment – for rainfall events with an average recurrence interval < 1 year sediment loads from low severity areas were reduced by 92%, 97% and 99% beneath 1 m, 5 m and 10 m wide unburnt patches, respectively. Thus, it seems that while there is little difference in sediment loads between the high and low fire severities, unburnt patches are important for reducing potential water quality impacts following prescribed burning. Fire managers should aim to maintain unburnt patches, especially towards the bottom of hillslopes.

Introduction

As governments set ambitious targets to increase prescribed burning (e.g. Parliament of Victoria 2010), it is important to understand and manage the potential effect on ecosystem services such as water supply. This paper considers the effects of prescribed burning on runoff and erosion. Runoff and erosion following fire can reduce water quality in streams and reservoirs (Smith *et al.* 2011), which is a problem for aquatic ecology (Minshall 2003) and human consumption (Smith *et al.* 2011). There is little research into the effects of prescribed burning on runoff and erosion in south-eastern Australia (e.g. Ronan 1986; Smith *et al.* 2010).

Forest fires increase runoff and erosion by removing vegetation, changing the soil's hydrologic properties, and providing a readily erodible layer of sediment and ash (see reviews by Certini 2005; Neary et al. 1999; Shakesby 2011; Shakesby and Doerr 2006; Shakesby et al. 2007; Wondzell and King 2003). The magnitude of post-fire runoff and erosion is determined by a combination of factors relating to the fire regime, post-fire rainfall and site characteristics (Figure 1). This study focuses on the effects of fire severity and burn patchiness – fire regime characteristics particularly relevant to prescribed burning.

Fire severity – a qualitative measure of the loss of organic matter caused by fire (Keeley 2009) – is considered one of the most important factors affecting post-fire runoff and erosion (Neary *et al.* 1999; Shakesby and Doerr 2006). The relationship between fire severity and post-fire runoff and erosion is thought to depend on the amount of soil heating during the burn (Doerr *et al.* 2006; Neary *et al.* 1999) and the loss of vegetative cover (Benavides-Solorio and MacDonald 2005). Overall, less runoff and erosion are reported for low fire severity areas than high severity areas (Benavides-Solorio and MacDonald 2005; Dragovich and Morris 2002; Robichaud 2000), or at least low severities are associated with soil properties less conducive to runoff and erosion (Doerr *et al.* 2006; Woods *et al.* 2007).

Patchiness influences the connectivity of runoff and erosion across a hillslope (Bracken and Croke 2007). Within a prescribed burn, different fire severities and unburnt areas create a mosaic of patches (Penman *et al.* 2007). Burnt patches are thought to act as sediment sources while unburnt patches act as sediment sinks. Several authors acknowledge the potential significance of burn patchiness to runoff and erosion (e.g. Benavides-Solorio and MacDonald 2005; Kutiel *et al.* 1995; Smith *et al.* 2010) and hydrologic modelling has demonstrated that some spatial arrangements of fire severities increase runoff connectivity (e.g. Moody *et al.* 2008; Robichaud and Monroe 1997).

A greater understanding of how fire severity and burn patchiness affects runoff and erosion could improve burning practices and reduce water quality impacts. This paper aims to assist fire managers by quantifying:

- the effect of prescribed fire severities on runoff and erosion, and
- the reduction in runoff and sediment caused by unburnt patches on burnt hillslopes.

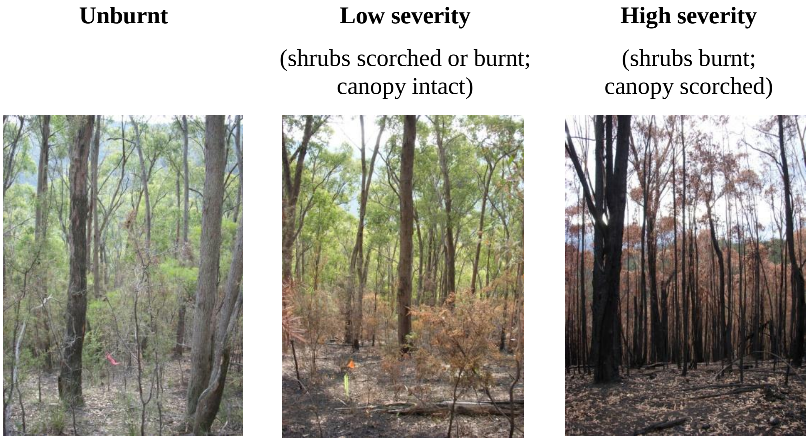
Fire regime	+	**Rainfall properties**	+	**Site characteristics**	=	**Magnitude of post-fire runoff and erosion**
Fire severity Patchiness Fire frequency Fire season		Rainfall total Rainfall intensity Rainfall duration		Slope gradient Flow convergence Aspect Soil type and geology Vegetation type		

Figure 1 Factors that determine the magnitude of post-fire runoff and erosion

Methods

Site description

The study site was on the north-facing slopes of McMahons Creek and Smoko Creek catchments, tributaries to the Upper Yarra catchment in Victoria (37^{o}43' S , 145^{o}51' N). The vegetation was shrubby foothill forest according to the Victorian Government's Ecological Vegetation Classification (www.dse.vic.gov.au). The soils were shallow (70 cm), clay-loam soil over a sedimentary substrate. The site was burnt by prescribed fire in April 2009. Fire severity was mostly low, with some high severity patches on the northerly aspects and ridges and large unburnt areas on the southerly aspects and in the gullies (Figure 2).



Unburnt

Low severity
(shrubs scorched or burnt; canopy intact)

High severity
(shrubs burnt; canopy scorched)

Figure 2: Unburnt, low severity and high severity on northerly aspects within the prescribed burn.

Field measurements

Unbounded samplers were used to measure the amount of surface runoff and sediment crossing a particular point on the hillslope from August 2009 (4-months post-burn) to December 2010 (20 months post-burn). Figure 3 illustrates the design of the samplers, which were installed in transects on planar hillslopes beneath six treatments: (1) high fire severity, (2) low fire severity, (3) unburnt, low fire severity above (4) 1 m, (5) 5 m and (6) 10 m wide unburnt patches (Figure 4 and 5). There were 20 samplers in each transect except for the 1 m unburnt patch treatment, which had 16 samplers. On 27 occasions runoff depth was measured in every sampler and sediment concentration in 50% of them if there was sufficient runoff. Rainfall was measured at 3-minute intervals with a weather station located within 2.5 km of the samplers.

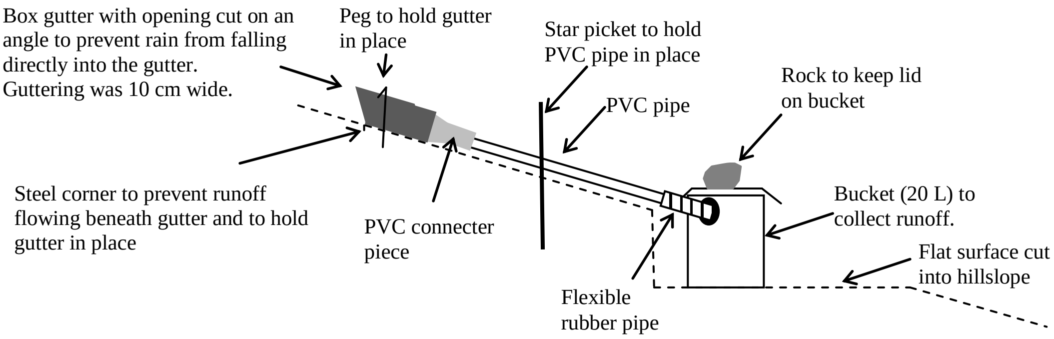


Figure 3: Design of the runoff samplers. Surface runoff and sediment were measured regularly following rainfall.

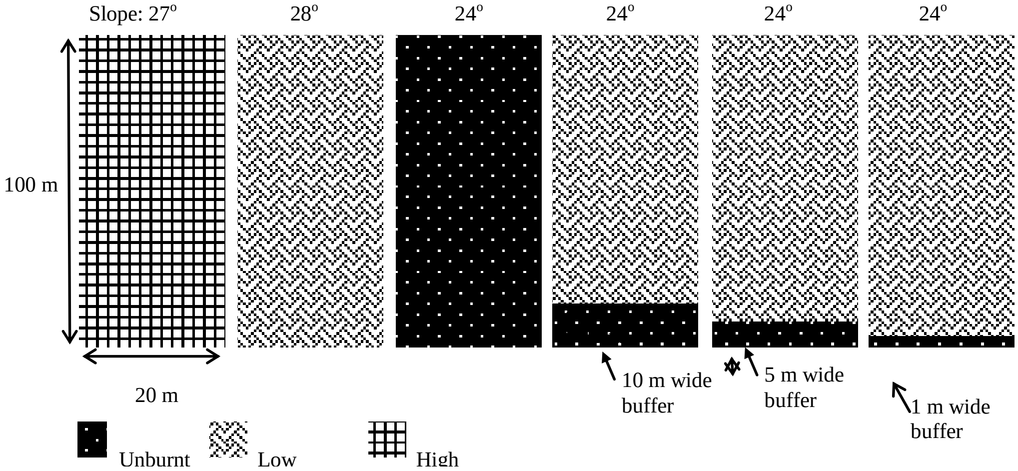


Figure 4: Patch arrangements above the runoff samplers. The low severity, 10 m buffered, 5 m buffered and unburnt transects were located side-by-side on the same hillslope. Slopes for each hillslope are shown above the diagram.

(a) High severity, August 2009 **(b) High severity, August 2010**

Figure 5: Transect of 20 runoff samplers on the high severity hillslope. Samplers were located 100 m from the ridge on planar hillslopes. The total length of the hillslopes was approximately 200-300 m.

Data analysis

Total runoff volume per metre width of hillslope was calculated for each treatment on each measurement date:

$$\text{Runoff total per metre width} = \frac{(\text{Sampler 1 vol.} + \text{Sampler 2 vol.} + \cdots + \text{Sampler } n \text{ vol.})}{(\text{no. samplers } \times 10 \text{ cm})} \times 100\ cm$$

If there were overflowing samplers (2.5% of the time) the total runoff volume was predicted from a linear regression between total runoff volume and the n^{th} percentile runoff volume for rainfall events when there were no overflowing tanks (Table 1). Runoff volumes were converted to runoff ratios by assuming a contributing hillslope length of 100 m – approximately the distance to the catchment divide from the samplers:

$$\text{Runoff ratio \%} = \frac{\text{runoff depth}}{\text{rainfall depth}} \times 100$$

Sediment load was calculated per metre width of hillslope for each treatment on each measurement date:

$$\text{Sediment load} = \text{Runoff total } \times \text{ mean sediment concentration}$$

For the hillslopes with 1 m, 5 m and 10 m unburnt patches (located below the low fire severity burns) the sediment trapping efficiency of the unburnt patch was calculated on each measurement date:

$$\text{\% reduction in sediment} = \frac{\text{sediment load beneath unburnt patch}}{\text{sediment load from low severity hillslope}} \times 100$$

Means and standard deviations were calculated for runoff volume, sediment concentration and sediment load. T-tests (two-tailed, unequal variances) were used to test the significance of differences between the means for each treatment. A function was found to describe the relationship between the width of the unburnt patch and its sediment trapping efficiency using Lab Fit Curve Fitting Software.

Table 1: Regression equations used to calculate the runoff total when there were overflowing tanks; y = the runoff total and x = the nth percentile runoff volume

Treatment	Regression equation	X	R^2
High severity	$y = 23.304 x + 5.4279$	60th percentile	0.7561
Low severity	$y = 44.832 x + 8.1642$	40th percentile	0.8235
1 m buffer	$y = 42.442 x + 0.8621$	60th percentile	0.8157
5 m buffer	$y = 17.167 x + 0.7692$	80th percentile	0.7337
10 m buffer	$y = 13.45 x + 0.7868$	80th percentile	0.8744
Unburnt	Not required – no overflowing tanks		

Results

The volume of runoff was approximately two orders of magnitude greater on the burnt hillslopes compared with the unburnt hillslope (44-45 L m-1 compared to 0.5 L m-1) while the annual sediment load was approximately four orders of magnitude greater on the burnt hillslope (1.3-1.5 kg m-1 compared to 8 x 10-4 kg m-1) (Figure 6 and

Table 2). In comparison, differences in runoff between the high and low fire severity hillslopes were small (44 L m^{-1} compared to 45 L m^{-1}). A slight difference in the mean sediment concentration between the fire severities (0.9 g L^{-1} compared to 0.6 g L^{-1}) resulted in cumulative sediment loads that were 13% larger on the high fire severity hillslope. Standard deviations were large, probably reflecting large differences in the rainfall events. T-tests showed significant differences between burnt and unburnt hillslopes but not between high and low fire severity hillslopes for runoff volume and sediment concentration. There were no significant differences between the sediment loads.

For most rainfall events (i.e. those with average recurrence intervals (ARI) < 1 year), there were distinct differences in sediment load between the uniformly burnt hillslopes and those with unburnt patches (Figure 6). The percentage reduction in sediment ranged from 92% to 99% depending on patch width, with higher percent reductions beneath wider unburnt patches. For an intense storm on the 27th November 2009 (I_{30} = 44 mm h^{-1}; ARI of 10 years) the 5 m and 10 m unburnt patches continued to be effective at reducing the sediment load, but the 1 m unburnt patch was ineffective yielding more sediment than the low severity hillslope. This rainfall event was highly influential overall in terms of the annual sediment loads for each hillslope treatment (Figure 6). The functions fitted in Figure 7 illustrate the effect of patch width on sediment load and the influence of rainfall properties.

Table 2: Summary statistics for the entire measurement period. Standard deviations are in brackets. Letters denote the outcome of statistical testing between treatments (i.e. values on the same line). Values which are not significantly difference share the same letter (t-tests; $p < 0.05$).

	Hillslope treatment					
	High severity	Low severity	Unburnt	1 m patch	5 m patch	10 m patch
Mean runoff volume (L m^{-1})	44 (50)a	45 (64)a	0.5 (0.7)b	23 (94)abc	6 (21)bc	2 (2.1)c
Mean runoff ratio (%)	0.86 (0.7)a	0.84 (1.0)a	0.01 (0.01)b	0.36 (1.5)abc	0.10 (0.3)bc	0.04 (0.1)c
Mean sediment concentration (g L^{-1})	0.9 (1.5)a	0.6 (0.9)a	0.04 (0.1)bc	0.3 (0.7)ab	0.09 (0.1)bc	0.04 (0.1)c
Mean sediment load (g m^{-1})	86 (295)a	70 (257)a	0.06 (0.3)a	69 (329)a	2 (9.4)a	0.2 (0.37)a
Total sediment load (g m^{-1})	2058	1671	1	1646	57	4
Mean annual sediment load (kg m^{-1} y^{-1})	1.5	1.3	8×10^{-4}	1.2	0.04	3×10^{-3}
Mean annual sediment load (kg ha^{-1} y^{-1})	154	125	0.08	123	4.3	0.3

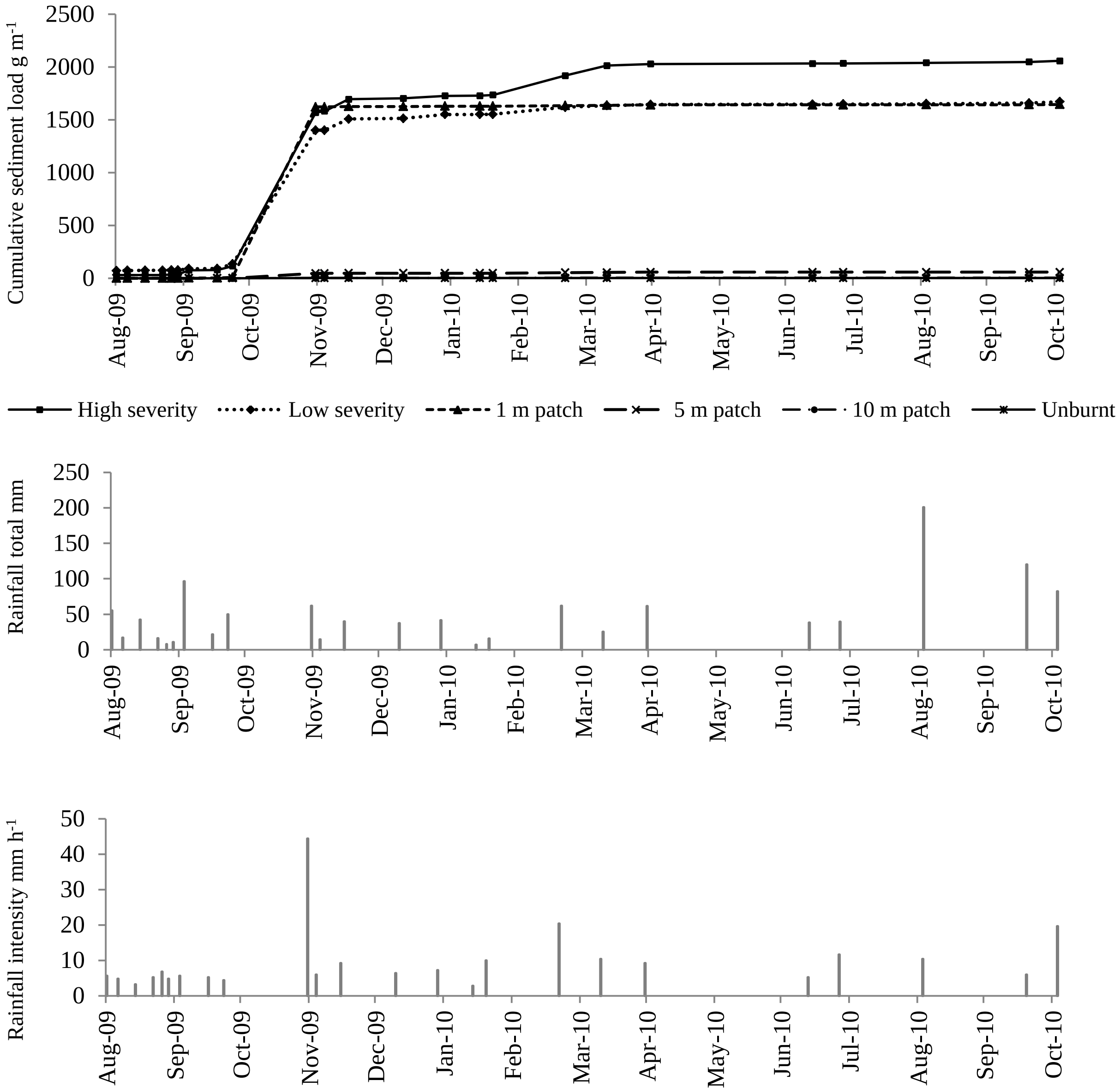


Figure 6: Time series charts showing (a) the cumulative sediment load; (b) the rainfall total contributing to each measurement date; and (c) the 30-minute maximum (I_{30}) rainfall intensity contributing to each measurement date.

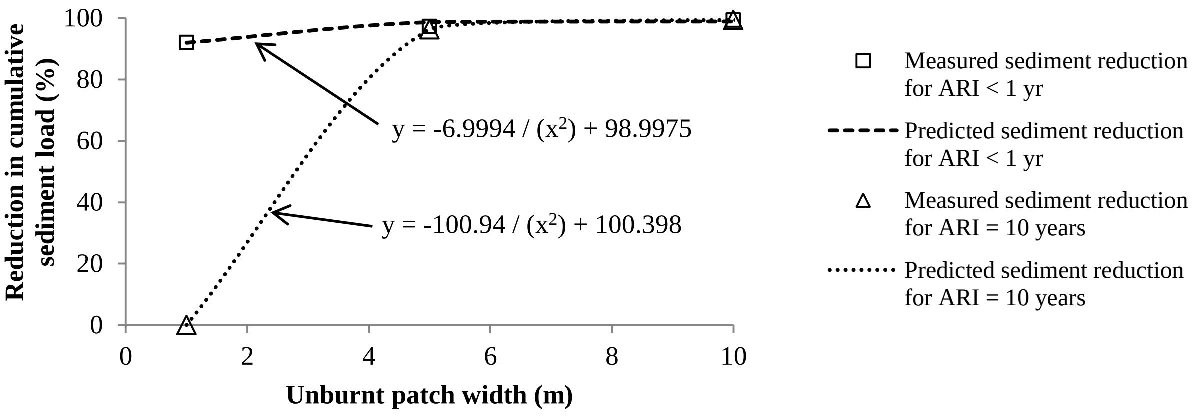


Figure 7: Relationship between unburnt patch width and percent reduction in sediment load relative to the low fire severity hillslope. Fitted curves are for the function y = a/(x^2) + b.

Discussion

The effects of fire severity on runoff and erosion

Runoff and erosion rates were minimal from the unburnt planar hillslope; the mean runoff ratio was 0.01% and the sediment load was 0.08 kg ha^{-1} y^{-1}. Other studies also report low runoff and erosion rates from unburnt eucalypt forests. Bren and Turner (1979) measured hillslope runoff ratios of < 0.5% in mixed-species eucalypt forest in north-eastern Victoria. Ronan (1986) measured mean runoff ratios of 0.5-1.3% and mean sediment loads of 0.12 - 0.19 t ha^{-1} y^{-1} for plots (20 x 20 m) in a mixed-species eucalypt forest in the Central Highlands of Victoria. Prosser and Williams (1998) measured hillslope sediment yields of 0.02 kg m^{-1} y^{-1} in a mixed-species eucalypt forest in the Blue Mountains, New South Wales. Given such low rates of hillslope runoff and erosion in unburnt forest, the catchment-scale contribution of runoff to instream suspended sediment loads (TSS) is likely to be low. Few studies report catchment-scale TSS loads for undisturbed eucalypt forests (Table 3). Of the catchments listed in Table 3, the Ella Creek catchment (Bren and Hopmans 2007), with its mixed-species eucalypt forest, probably most resembles the Upper Yarra study site. Assuming the TSS load at the Upper Yarra site were similar to that of Ella Creek (i.e. 0.007 t ha^{-1} y^{-1}), then the hillslope contribution to the TSS load (i.e. 0.08 kg ha^{-1} y^{-1}) would be approximately 1%. This suggests that hillslope runoff is unimportant to TSS loads in undisturbed forest catchments.

Table 3: Total suspended sediment loads (t ha-1 y-1) for undisturbed forest catchments in Victoria

Location	Dominant vegetation type	Sediment load (t ha^{-1} y^{-1})	Author
Upper section of the Tyers River catchment (13,451 ha) on the southern face of Mt Baw Baw in the Victorian Central Highlands.	Ash eucalypt forest (wet)	0.085 Sampling over one year	Sheridan and Noske (2007)
Ella Creek catchment (113 ha), a tributary to the Buffalo river in north-eastern Victoria.	Mixed-species eucalypt forest (dry)	0.0074 Sampling over six years	Bren and Hopmans (2007)
Stony Creek (75 ha), a tributary to the Latrobe River in the Victorian Central Highlands	Ash eucalypt forest (wet)	0.024 Sampling over five months	Lane and Sheridan (2002)
Sub-catchment (25 ha) of Myrtle Creek in the Maroondah catchment area of the Victorian Central Highlands	Ash eucalypt forest (wet)	0.076 Sampling over 10 years	Grayson *et al.* (1993)

Differences in hillslope runoff and erosion between burnt and unburnt areas were substantial. Annual sediment loads on the burnt hillslopes (125-154 kg $ha^{-1}y^{-1}$) were approximately three orders of magnitude larger than on the unburnt hillslope (0.08 kg $ha^{-1}y^{-1}$). Other studies also report large increases in runoff and erosion in burnt areas (as reviewed by Certini 2005; Shakesby and Doerr 2006; Smith *et al.* 2011). For mixed-species eucalypt forest, Prosser and Williams (1998) found that sediment yields increased by approximately one order of magnitude following burning, while Ronan (1986) found that they increased by approximately two orders of magnitude. The significance of those increases at the catchment scale depends on the relative contribution of hillslope runoff and erosion to instream TSS loads. By using the Ella Creek catchment (Bren, 2007) as an example, the effect of burning on catchment-scale TSS loads can be estimated. If burning within the Ella catchment resulted in similar amounts of surface runoff and erosion to burning in the Upper Yarra catchment (i.e. an erosion rate of 125-154 $kg^{-1}ha^{-1}y^{-1}$), then burning the entire catchment could increase the instream TSS load by approximately two orders of magnitude (from 0.007 t ha^{-1} y^{-1} to approximately 0.132-0.161 t ha^{-1} y^{-1}). Such large increases could have water quality implications.

The sediment concentration from the high fire severity hillslope was larger than from the low fire severity hillslope, resulting in different sediment loads (154 kg m^{-1} y^{-1} compared to 125 kg m^{-1} y^{-1}). However, those differences in concentration and load were not statistically significant. Other studies also report higher sediment loads for high fire severity areas (e.g. Benavides-Solorio and MacDonald 2005; Dragovich and Morris 2002; Inbar *et al.* 1998). Benavides-Solorio and Macdonald (2005) reported hillslope sediment loads that were 40-200 times larger for high compared to low fire severity in the Colorado Front Range, USA. Inbar *et al.* (1998) reported hillslope sediment loads that were 156 times larger for high compared to low fire severity at Mt Carmel in Israel. Dragovich and Morris (2002) reported hillslope sediment loads were two times greater for high compared to moderate fire severity hillslopes. The differences reported in the literature between fire severities are generally much larger than those measured in this study, which suggests that the hydrologic properties of the fire severities in this study were similar. Also, the hillslopes in this study were planar, which may have reduced the relative difference in erosion rates between the fire severities.

The effect of unburnt patches on runoff and erosion connectivity on a burnt hillslope

Unburnt patches were extremely effective at reducing runoff and erosion from burnt hillslopes – for rainfall events with an ARI < 1 year the sediment loads from the unburnt patches were 92%, 97% and 99% smaller than from the low severity hillslope for the 1 m, 5 m and 10 m patches, respectively. There was a clear relationship between patch width and the percentage reduction in sediment load. For higher rainfall intensities, the 1 m patch was less effective at reducing the sediment load – i.e. for the 27th November 2009 rainfall event (ARI = 10 years) there was no reduction in the sediment load. Other studies also report reductions in sediment loads beneath vegetated patches (Cerdà 1997; Dosskey 2001; Helmers *et al.* 2005; Mayor *et al.* 2009), though there are no similar studies in burnt environments. In a semi-arid environment Bartley *et al.* (2006) reported a hillslope runoff ratio of 71% when there was a large bare patch near the base of the hillslope, compared with a runoff ratio of 8% for a hillslope with uniformly distributed bare and vegetated patches. In modelling simulations, Reaney (2003) predicted that no runoff would reach the bottom of a hillslope if there was a five metre vegetated strip at its base during 75 mm h^{-1} rainfall lasting for five minutes. In tree belts across pastoral land Leguédois *et al.*(2008) reported that sediment loads were reduced by 90% below the tree belts.

The results of this study suggest that unburnt patches play an important role in reducing connectivity between burnt patches and streams, thus ultimately reducing water quality impacts following prescribed burning. The simplified diagram in Figure 8 demonstrates this by depicting the potential influence of different unburnt patch arrangements on runoff and erosion connectivity for planar hillslopes. For each scenario 80% of the hillslope is burnt and 20% is unburnt. The unburnt patches are wide enough to reduce sediment transport from the burnt areas above by 100%. The percentage values are the potential burnt area connected to the stream – note that the actual burnt area contributing runoff and erosion to the stream is likely to be less than the potential area due to interception by obstacles or deposition when the sediment weight exceeds the energy of the overland flow. This connected area varies as a function of rainfall intensity. The diagram shows that while unburnt patches anywhere on the hillslope reduce the amount of burnt area potentially connecting to the stream, those patches near the bottom of the hillslope are likely to have the greatest effect. Prescribed burns often have unburnt patches, especially in riparian zones (Penman *et al.* 2007). This may explain why large increases in TSS loads are rarely reported following prescribed burning. This research demonstrates the importance of maintaining a mosaic of unburnt patches throughout a prescribed burn, particularly at the bottom of the hillslope, to reduce water quality impacts.

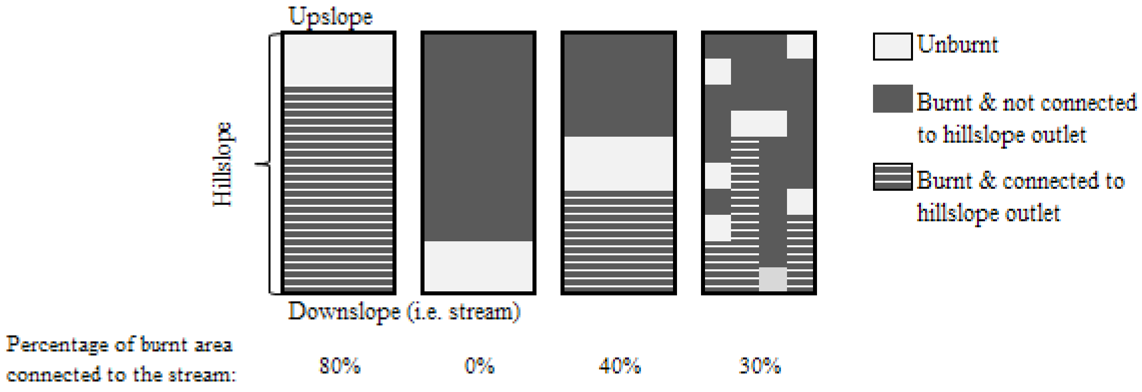


Figure 8: Percentage of burnt area potentially connected to a stream for different unburnt patch arrangements on planar hillslopes. For each hillslope 80% is burnt and 20% is unburnt. Unburnt patches reduce runoff and erosion from above by 100%.

Conclusion

Prescribed burning increased the annual hillslope sediment load by approximately four orders magnitude from 8 x 10^{-4} kg ha^{-1} to 1.3-1.5 kg ha^{-1}, but the relative difference in sediment loads between the high and low fire severity hillslopes was only 13%. The implications for water quality are potentially very large – e.g. burning could cause a 100-fold increase in annual instream TSS if the entire catchment were burnt. However, in reality prescribed burns are often patchy. Unburnt patches on a burnt hillslope are highly effective at reducing runoff and sediment from burnt areas above –for rainfall events with an ARI < 1 year, sediment loads were reduced by 92-99% when there were unburnt patches beneath a burnt hillslope compared to hillslopes with no unburnt patches. Thus the potential for water quality impacts from prescribed burning is greatly reduced by the presence of unburnt patches, particularly near the bottom of the hillslope.

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